Innovation dynamics induced by environmental policy: Final report

Oosterhuis, F.H.; Kuik, O.J.; Berkhout, F.G.H.

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Final report

Edited by Frans Oosterhuis (IVM)

Contributions by:

Onno Kuik and Frans Berkhout (IVM)

Andrew Venn and Paul Ekins (PSI)

Jason Anderson, Samuela Bassi, Emilia Stantcheva and Patrick ten Brink (IEEP)

Jan Ros (MNP)

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IVM

Institute for Environmental Studies
Vrije Universiteit
De Boelelaan 1087
1081 HV Amsterdam
The Netherlands

Tel. ++31-20-5989 555
Fax. ++31-20-5989 553
E-mail: info@ivm.falw.vu.nl

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Preface and acknowledgements

This report is the result of a project under the ‘Framework contract for economic analysis in the context of environmental policies and of sustainable development’ (ENV.G.1/FRA/2004/0081). The objective of this project (specific agreement no. 07010401/2005/424497/FRA/G1) was to analyse (using specific case studies) how environmental policy induces innovation and to provide an analysis of the dynamics of this innovation.

The project was carried out by IVM (coordinator), PSI, IEEP and MNP. The Commission’s contact person was Jakub Koniecki. The authors want to thank the many people who provided valuable suggestions and information, including the participants in the expert workshop that took place on 21 June 2006.

Summary

Environmental technologies (or 'eco-innovations') have the potential to sidestep the classic dilemma between economic growth and environmental improvement, by offering cost-effective solutions to environmental problems and export opportunities. The importance of eco-innovations is widely acknowledged, but its dynamics are as yet not fully understood.

The present study aims at analysing:

- How different environmental policy instruments induce innovation and to provide an analysis of the dynamics of this innovation;
- To what extent market-driven innovation can lead to lowering environmental impacts of products and processes.

The findings of this study are based on a literature survey, five case studies (on car fuel economy; energy efficiency of electronic office appliances; solar photovoltaics; emissions from pulp and paper production; and substitution of chemical substances) and an expert workshop.

There are several ways of distinguishing types of of (eco-)innovations, e.g.:

- 'Incremental' versus 'radical' ('breakthrough') innovations;
- Small-scale versus large-scale innovations (the latter, also known as 'transitions', affecting complete socio-technical systems);
- 'End-of-pipe' versus 'process integrated' environmental technology, as well as product innovations;
- 'Policy driven' versus 'business/market-driven' eco-innovations.

The main determinants of investing in R&D are technological opportunities; market demand and other economic stimuli; and 'appropriability conditions' (such as patents). The main factors behind the adoption of a new technology include the price and quality of the innovation; knowledge and information; and risk and uncertainty. Regulation can be seen as a separate important factor. Obviously, there are also many possible barriers to innovation. The evolutionary economics school of thought emphasises path dependence and increasing returns to scale, which may result in 'lock in' in certain technologies.

The market penetration of new technologies often follows a pattern in which the uptake starts at a low speed, then accelerates and slows down again when the level of saturation approaches (logistic or S-curve). The acceleration in uptake is partly the result of cost reductions due to 'learning curve' effects: higher levels of (accumulated) production lead to lower unit costs. Evidence from our case studies shows that costs decrease by 20 to 30 percent for each doubling of accumulated production. However, caution is needed when using such figures to predict cost reductions without a good understanding of the dynamics behind them.

It is widely acknowledged that environmental policies have the potential to exert a strong influence on both the speed and the direction of environmental innovation, next to other factors such as market demand, competition and costs. This is confirmed by the literature and the case studies that have been reviewed in the present study. However, the evidence for the

statement that such policies lead to a higher overall level of innovativeness and competitiveness (as reflected in the "Porter hypothesis') is not unequivocal. Furthermore, ill-designed environmental policies can also have a counterproductive impact on innovations (an example is the so-called 'new source bias', which results from regulations which impose stricter demands on new sources than on existing sources).

No general statements can be made about the kind of policy instruments that are best suited to support the development and diffusion of environmental technology. Economic instruments are often seen as superior to direct regulation, because they provide an additional and lasting financial incentive to look for 'greener' solutions. Nevertheless, under certain conditions (such as a monopolistic market) direct regulation may perform better. Direct regulation may also be a powerful instrument if firms expect that the new technology will become the basis for a future standard (e.g. BAT), so that they can sell it on the (world) market. Furthermore, economic instruments may be less appropriate if the main factor blocking eco-innovation is not a financial one. Direct R&D support and voluntary instruments can play a role as well.

In general, the appropriateness of particular instruments may depend on the purpose for which they are used (e.g. innovation or diffusion) and the specific context in which they are applied (see Table S.1). In practice, combinations of different instruments will often be used, implying that the impacts of interactions between them also need to be addressed. Finally, the *design* of an instrument may be at least as important as the instrument type. One type of instrument can produce widely different results when applied differently. The real design of environmental instruments is influenced by the policy process, and it may deviate considerably from the theoretical 'ideal type' of the instrument.

The study concludes that environmental policy's role in innovation is a steering one, rather than braking or driving. In this role, it is only one among many other factors determining the direction of industry's innovation efforts. The relative importance of this role differs from case to case. Those other factors may or may not steer the innovation process in the same direction as the environmental policy maker has in mind. Synergies and 'autonomous' trends towards cleaner technology do occur, but are by no means guaranteed. Innovation-oriented environmental policy will therefore remain essential for sustainable technological development.

Inducing innovation requires strong policy: the objectives and instruments should make it clear that significant changes are needed. Weak policy, whether in terms of weak standards (e.g. car fuel economy standards in the USA), or insufficient financial incentives (e.g. solar PV support in the UK) will not be likely to achieve it. Nevertheless, a careful balance has to be found between ambition and realism, so as to ensure that there are lasting incentives for innovation but also achievable opportunities and sufficient competition. Continuous improvements in BAT and other benchmarks could be realised by introducing obligations to look for new technological opportunities, even beyond the borders of the own industry. On the other hand, radical innovations may require strong direct support for emerging technologies (often developed outside the vested firms) that pose a challenge to the existing 'locked in' technology.

Table S.1 Instruments, characteristics and context of the innovation

Instrument type	Type of innovation	Innovation factors/barriers	Stage in innovation process/cycle
Direct regulation			
Emission standards (mandatory)	Process	Technological opportunities exist, but lack of market demand	All
Product standards (mandatory)	Product	Technological opportunities exist, but lack of market demand	All
Economic instruments			
R&D support	Product and process	Lack of technological opportunities; lack of appropriability conditions; perceived risk	R&D stage
Public procurement	Product	Latent market demand, but barriers for massive uptake (e.g. risk, price)	Niche market / early adopters stage
Emission charges / tradable permits	Process	Technological opportunities may exist, but cost barrier to uptake; or they may not exist (then the economic incentive will stimulate searching for them)	All
Financial incentives stimulating market demand	Product	Latent market demand, but price/cost barrier	Niche market / early adopters stage
Information and communication			
(Eco-)labelling	Product	Latent market demand, but information barrier	Early adopters / mature market stage
Voluntary agreements	Product and process	Various	All
No public intervention			
None (market can do the job on its own)	Product and process	No barriers	All

Obviously, with markets becoming increasingly globalised, there is no guarantee that the innovations induced by European environmental policy will also take place in European industry. On the other hand, however, there are several examples of domestic innovations (developed in response to environmental policy) that became successful export items as a result of similar policies implemented abroad.

The implications of this study's findings for the 'Innovation' part in Impact Assessments of new EU environmental policy proposals can be summarised as follows. Environmental policy will in general not be an obstacle to R&D. A policy option's chance of stimulating R&D is likely to be greater if it provides a clear, consistent and lasting incentive to develop and adopt innovative solutions. It should be challenging and feasible at the same time. The extent to which a new policy measure will facilitate the introduction and dissemination of new production methods, technologies and products depends on the choice and design of the policy instrument(s). There is no evidence for any impact of environmental policies on intellectual property rights. Finally, environmental policy will usually contribute to improving resource efficiency, as this is often the explicit aim of such policy.

1. Introduction

Environmental technologies are a key element in the quest for sustainable development. They have the potential to sidestep the classic dilemma between economic growth and environmental improvement. In the past, numerous new technologies have been introduced in the EU that have contributed to pollution prevention, environmental clean-up, and the conservation of energy and resources. Moreover, many of these have led to reductions in costs and/or reinforced the competitive strength of EU industry, as 'clean' technologies that were developed in Europe became successful export products on the world market after some time.

The important role of environmental technologies (or 'eco-innovation') is recognised by the European Commission. In January 2004, the 'Environmental Technologies Action Plan' (ETAP)[1] was presented. It aims to harness the full potential of environmental technologies to reduce pressures on natural resources, improve the quality of life and stimulate economic growth. The ETAP contains a number of concrete actions that are intended to help achieve this aim.

The mechanisms behind the development and diffusion of technologies and products that lead to lower environmental impacts are still not fully understood. In particular, the actual and potential role of different instruments of environmental policies (including EU policy) deserves closer investigation. In order to do so, it is important to study the theory of 'green' innovation dynamics as well as practical experiences with the use of policies to promote environmental technology. Moreover, attention should be paid to the potential role of market-driven technological change (not primarily motivated by environmental concerns), which often also result in lowering pressure on the environment.

Against this background, the objective of the research project of which the present report summarizes the results was to analyse:

- How different environmental policy instruments induce innovation, and to provide an analysis of the dynamics of this innovation;
- To what extent market-driven innovation can lead to lowering environmental impacts of products and processes.

The term 'innovation' is used in a broad sense throughout this study, including not only the invention and development of new technologies, products and practices, but also their diffusion (uptake and market penetration), including the modifications that usually occur during that diffusion process.

The study included the following elements:

- A literature survey, reviewing studies relating to practical application of eco-innovation and the effect of policy implementation on eco-innovation and development of environmental technologies;

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1 COM(2004)38 final.

- Five case studies, addressing different types of innovation and different policy instruments[2];
- An expert workshop, in which the preliminary results of the literature survey and the case studies were discussed and some additional views on the relationship between environmental policy and innovation were presented.

This report integrates the findings from all three elements of the project. It is structured as follows. In chapter 2, the concept of eco-innovation is discussed, different types of innovation are distinguished, and the dynamics of the innovation process are analysed. Chapter 3 addresses the role of environmental policy in (eco-)innovation in a general sense. Chapter 4 deals with the various types of policy instruments and their possible role in different contexts and different stages of the innovation process. Chapter 5 presents conclusions and policy implications, with specific attention for the design of policy instruments and for the way in which impact assessments of environmental policy could deal with innovation aspects.

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2 The case studies related to (1) car fuel economy and CO_2 emissions; (2) energy efficiency of electronic office appliances; (3) solar photovoltaics; (4) emissions from pulp and paper production; and (5) substitution of chemical substances. Appendix I summarizes the case study findings. Complete case study reports are available as separate documents.

2. The dynamics of (eco-)innovation

2.1 Types of innovation

Innovations in environmental technology (or 'eco-innovations') display many features of 'ordinary' innovations, but they have an additional characteristic in that their application may reduce certain negative environmental impacts (including resource use).

A 'general' feature of innovations that is also relevant for eco-innovation is the extent to which the innovation implies changes in inputs, capital goods, skills required, organisational routines, links with suppliers and customers, etcetera. An innovation can be 'incremental' (small changes to an existing process or product, not affecting existing routines) or they may have a 'radical' ('breakthrough') character, implying fundamental changes in an existing system. Obviously, these are two extreme types and many innovations will be somewhere in between them.

Furthermore, the scale of an innovation is important. Small-scale innovations may only have consequences for a specific firm, industry, or production process, or for a particular product or group of consumers. At the other extreme, there are large scale innovations which affect complete socio-technical systems (these are sometimes called 'transitions').

A specific feature of environmental technology is the particular mechanism by which the environmental impact is reduced. The following types are often distinguished:

- 'End-of-pipe' technology (isolating or neutralizing polluting substances after they have been formed). End-of-pipe technology is often seen as undesirable because it may lead to waste that has to be disposed of.[3]
- 'Process-integrated' technology, also known as 'integrated' or 'clean' technology. This is a general term for changes in processes and production methods that lead to less pollution, resource and/or energy use.
- Product innovations, in which (final) products are developed or (re)designed that contain less harmful substances, use less energy, produce less waste, etcetera.

It is sometimes argued that there is a 'natural' tendency for environmental technology to develop from abatement (end-of-pipe) to 'integrated' (clean) technologies. This view is, however, challenged by Berkhout (2005). Frondel *et al.* (2004) also point out that a certain amount of end-of-pipe technologies will remain necessary to curb specific emissions which cannot easily be reduced with cleaner production measures.

In addition to the three types mentioned above, organisational changes are sometimes distinguished as a separate kind of (eco-)innovation. However, it is probably more appropriate to say that organisational changes are complementary to technical changes in most types of (eco-)innovation processes, even though there are of course cases where

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[3] This is not necessarily the case, though. For example, reducing nitrogen oxides at the end of a smokestack or car exhaust produces the harmless substances nitrogen and oxygen, which are natural components of the air.

organisational measures can lead to improvements (e.g. through more efficient logistics) without any changes in the technical 'hardware'.

Environmental innovations can be either primarily 'policy driven' or primarily 'business/market-driven'. Obviously, end-of-pipe technology will usually be primarily policy-driven, as such technology merely adds to the cost of the production process. Process and product innovations, however, tend to come about as part of the 'normal' business cycle, because such innovations may lead to cost reductions, improved processes and/or better market opportunities. For such innovations, environmental policy tends to be just one among the many factors that steer, accelerate, or set the conditions for the innovation process.

2.2 Determinants of innovation

In the past, economists studying technical change have been fiercely debating the main determinants of innovation. On the one hand, the '(neo-)Schumpeterian' school emphasised the importance of new knowledge and technological opportunities (the 'supply push' view); on the other hand, there were those who stressed the role of market demand and other economic stimuli (the 'demand pull' view). Nowadays, there seems to be growing consensus that both types of factors are important, even though their relative importance may differ from case to case.

A third factor contributing to a successful innovation are the 'appropriability conditions' (Dosi, 1988): the means by which the innovating firm can reap the benefits of its innovation and protect it against imitation. Important appropriability conditions are lead times, learning curve effects (see section 2.3), secrecy and patents.

Besides these three factors, which are mainly relevant for the decision to invest in R&D, one can distinguish factors determining the likelihood of a firm or a consumer to purchase a new product or to invest in a new process that is available on the market. Kemp *et al.* (1992) mention three categories of relevant factors:

- Price and quality of the innovation;
- Knowledge and information;
- Risk and uncertainty.

In addition, Kemp *et al.* mention regulation as an important factor influencing the development and adoption of clean technology.

Recently, evolutionary approaches have received much attention in the explanation of innovation processes. This school of thought emphasises the dynamic mechanisms involved and the role of two opposing forces: innovation (leading to more diversity) and selection (leading to less diversity). Evolutionary economists argue that due to path dependence and increasing returns to scale society can become 'locked in' in certain technologies, even though better technologies are available (see e.g. Van den Bergh *et al.*, 2005). In this perspective, policy makers have an important role to play in preventing lock-in, maintaining diversity, and influencing the selection environment (e.g. by creating niche markets).

2.3 Stages in the innovation process

2.3.1 Literature findings

New technologies, when they are successful in being applied and finding their way to the market, often follow a pattern in which the uptake starts at a low speed, then accelerates and slows down again when the level of saturation approaches. This is reflected in the well-known logistic or S-curve (see Figure 2.1).

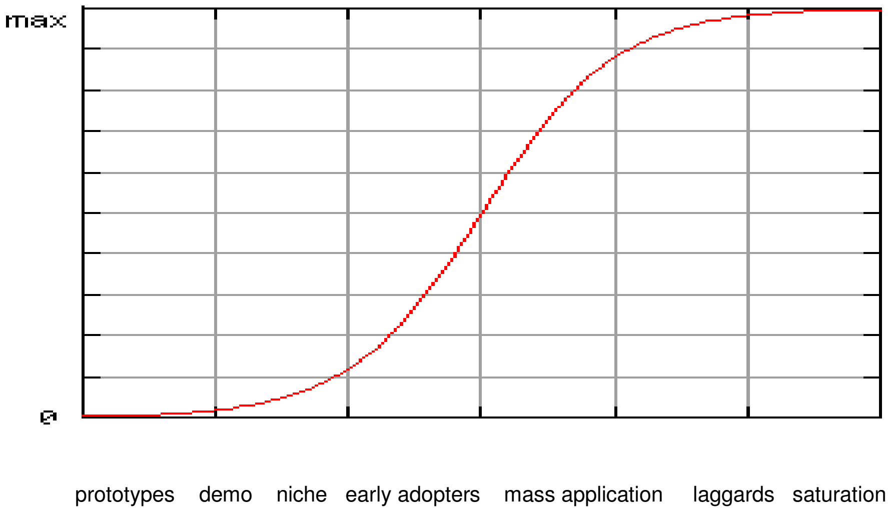

Figure 2.1 Stages in the introduction of a new technology; the S-curve.

The acceleration in uptake is not only due to the fact that the technology is becoming more widely known, but also to improvements and cost reductions occurring in the course of the diffusion process due to economies of scale and learning effects. Cost reductions as a function of the accumulated production (or sales) of a particular technology can be represented by 'learning curves' or 'experience curves'. The learning curve can be expressed in a general sense as:

$$Cost(CUM) = Cost_o * CUM^b \tag{2.1}$$

in which:

Cost(CUM) = the cost per unit as a function of cumulative production/shipments;

$Cost_o$ = the cost of the first unit produced/shipped;

CUM = cumulative production/shipments over time

b = the experience index.

The 'learning rate' is the percentage cost reduction with each doubling of cumulative production or sales. The relationship between the learning rate (LR) and the experience index (b) is defined as:

$$LR = 1 - 2^b \tag{2.2}$$

The term 2^b in this formula is also known as the 'progress ratio' (PR).

The IEA (2000a) has assessed the potential of experience curves as tools to inform and strengthen energy technology policy. It stresses the importance of measures to encourage niche markets for new technologies as one of the most efficient ways for governments to provide learning opportunities.

McDonald and Schrattenholzer (2001) have assembled data on experience accumulation and cost reduction for a number of energy technologies (including wind and solar PV). They estimated learning rates for the resulting 26 data sets, analyzed their variability, and evaluated their usefulness for applications in long-term energy models.

Junginger (2005) applied a learning curve approach to investigate the potential cost reductions in renewable electricity production technologies, in particular wind and biomass based. He also addressed a number of methodological issues related to the construction and use of learning curves.

Several authors have pointed to the fact that innovation is not a one-directional process following a fixed order of successive stages. Instead, innovation should be seen as a cyclical process in which experiences with new technologies lead to new changes (e.g. improvements in the new technology itself, new organisational routines and structures, or adaptations in behaviour). Such changes may imply a 'jump back' to an earlier stage of the innovation process.

2.3.2 Evidence from the case studies

The case of photovoltaic (PV) energy provides the best 'textbook' example of a learning curve, with a learning rate of 20% giving an excellent curve fit (see Figure 2.2).

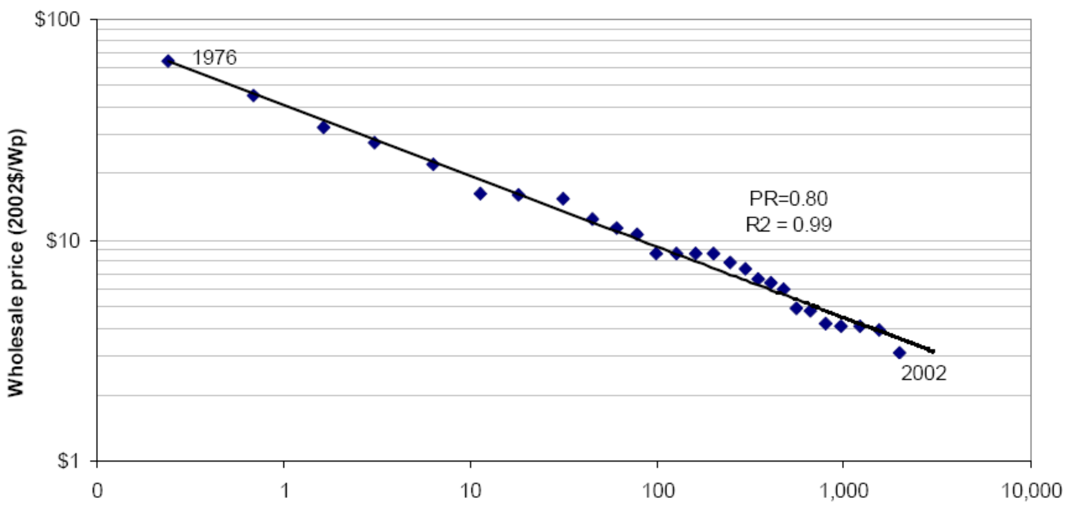

Figure 2.2 Experience curve for PV (Johnson, 2002; Dunay, 2003).

However, the case study also notes that learning derived from experience is only one of several explanations of the change in the main factors affecting the manufacturing cost of PV. This suggests cautious consideration of the conditions under which experience curves can be relied upon to predict technical change and cost decreases. It is important to understand the dynamics behind the cost reductions. The most influential factors in

PV cost reductions have had little to do with learning by doing as such, but rather with demand pull, R&D, and spillovers from other industries (Nemet, 2005).

The PV case also noted that the potential of technologies currently at an earlier stage (such as so-called third generation solar PV based on polymers and nanomaterials) should be recognised. These could potentially overcome today's technologies and offer lower cost options – creating a noticeable discontinuity in the learning curve (but with much uncertainty). Whether investing in 'breakthrough' technologies is worthwhile can be estimated on the basis of the price of the investment for the new technology, the probability that the investment in that technology will yield results (insofar as this is possible to know), and the estimated performance of the resulting product. This can then be compared to the trend in the existing experience curve to see how much investment would be needed to reach the point where the performance of the current technology is exceeded.

In the chemicals substitution case, it appeared that empirical evidence on the dynamics of costs and prices in the innovation of chemical substances is scarce. The main source (Lieberman, 1984) reported learning rates of 20 to 30%. Individual learning curves for the various substances were remarkably uniform, although there were some small but significant differences. In particular, R&D expenditures (or the underlying technological opportunities) appeared to steepen the learning curve. In the long term, prices of chemicals closely followed the learning curve, but in the short term market power led to a slow-down in price decreases, as might be expected.

Innovation in office appliances appeared to be less suitable for a 'learning curve' type of analysis. Energy efficiency is usually embedded in a large 'package' of features that characterize a new type of office appliance. This makes it impossible to isolate the development of costs of energy efficient innovations in this area. Generally speaking, the market for office electronics is very dynamic and prices of innovative products tend to drop quickly. Often the additional costs of incorporating energy efficient features in office appliances are close to zero.

3. The relationship between environmental policy and innovation

3.1 Literature findings

There is widespread agreement among the authors of influential articles and books on the subject that environmental policies have the potential to exert a strong influence on both the speed and the direction of environmental innovation. Rather than being an autonomous, 'black box' process, technological development is nowadays acknowledged to be usually the resultant of a large number of different factors that can be analysed, at least in principle. Environmental policy can be one of these factors, even though its relative importance may differ from case to case. The impact of environmental policy on innovation has been studied in various ways, both theoretically (often using models that incorporate technical change as an endogenous rather than as an exogenous variable) and empirically.

Box 3.1 How to measure innovative activity

If one wants to study the impact of (environmental) regulation on innovation, it is clearly desirable to have an objective measure of innovative activity. Unfortunately, no perfect measure exists, and empirical analyses have to use indicators such as R&D expenditures (an 'input' indicator) or patent registrations (an 'output' indicator). Each indicator has its drawbacks, both with respect to the accuracy in measuring environmental innovation and with respect to data availability and comparability.

A more extensive discussion on the issue of eco-innovation indicators can be found in a recent report by the European Environment Agency (EEA, 2006).

A landmark in the discussion on environmental regulation, innovation and industrial competitiveness is the famous 'Porter hypothesis'. Porter and Van der Linde (1995) state that "a truly competitive industry is more likely to take up a new [environmental] standard as a challenge and respond to it with innovation." Empirical tests of the 'Porter hypothesis' have led to mixed results (which seems at least partly due to different interpretations of the hypothesis; see e.g. Wagner, 2003). Jaffe and Palmer (1997) found no statistically significant relationships between regulatory compliance expenditure and patenting activity. However, they did find a significant positive relationship between regulatory compliance expenditures and R&D expenditures by the regulated industry (controlling for industry-specific effects), although the magnitude of the effect was small.

Jaffe *et al.* (2002) distinguish two major strands of thought regarding the determinants of innovative activity: the 'induced innovation' and the 'evolutionary' approach. They argue that only the second approach allows for 'win-win' solutions à la Porter.[4] They state

[4] The thinking being that if there are win-wins potentially available, then there would be no need for inducements. Others argue that there are win-wins that are not picked up without external help given information barriers or other barriers (time, limits to reward systems).

that empirical analysis of policy impact on innovation mainly exists in the area of energy efficiency.

Berkhout *et al.* (2003) studied the potential impact of the proposed new EU chemicals legislation (REACH) on innovation, competitiveness and employment. They conclude that many of the main provisions of the REACH proposals will tend to promote innovation, both within the EU chemicals sector and more widely. They add that the expected positive impacts on industrial innovation may take some time to show through.

Krozer (2002) investigated the extent to which environmental innovations can be introduced at socially acceptable costs, and what policies are needed to stimulate this. He developed a method to estimate cost functions and to identify (using these functions) areas where R&D investments in cost reducing innovations will be attractive. The importance of policy features that create better sales conditions for environmental innovations is emphasised. These include: timely announcement, the assurance of strict demands, and fast implementation.

Montalvo (2002) addresses the subject from a firm behaviour perspective. Leaning upon Ajzen's 'Theory of Planned Behaviour' he distinguishes three types of factors determining a firm's willingness to invest in cleaner technology: its attitude (determined by perceived risks), social pressures (including regulation), and control (the technological and organisational capabilities of the firm). His findings (based on a study of the '*maquiladoras*' firms located near the Mexico-US border) suggest that the third factor has the biggest influence, which would imply that reinforcing the cleaner technology knowledge base in enterprises should be the main policy priority.

The significance of environmental policies in driving eco-innovation is usually confirmed by empirical studies. Lanjouw and Mody (1996) presented evidence on environmental innovation and diffusion over the 1970s and 1980s. In the United States, Japan, and Germany, the share of environmental patents in all patents was higher than the corresponding share of pollution abatement expenditure in GDP. Across these three countries and over time, innovation responded to pollution abatement expenditure, an indicator of the severity of environmental regulations.

Pickman (1998) conducted an empirical study of the US manufacturing industry's environmental patent activities and environmental regulation as measured by pollution abatement and control expenditure (PACE) data. She finds a statistically significant positive relationship between environmental regulation and innovation using a two-staged least squares estimation procedure. Thus, Pickman concludes that there is evidence that innovation is a response to environmental regulation.

Kemp (2000) concludes from the available literature that the technology responses to environmental policy range from the diffusion of existing technology, incremental changes in processes, product reformulation to product substitution and the development of new processes. The most common responses to regulation are incremental innovation in processes and products and diffusion of existing technology (in the form of end-of-pipe solutions and non-innovative substitutions of existing substances). Often, the new technologies are developed by firms outside the regulated industry. The studies reviewed by Kemp also show, unsurprisingly, that the stringency of the regulation is an important determinant of the degree of innovation, with stringent regulations such as product bans being necessary for radical technology responses. Technology-forcing standards appear to be a necessary condition for bringing about innovative compliance responses.

Newell *et al.* (2002) used a 'product characteristics' approach to analyse the influence of energy prices and other factors on the energy efficiency of air conditioners and water heaters. Besides energy prices, government energy efficiency standards also had a significant impact on the average energy efficiency of the models offered for sale.

Similä (2002) shows that regulation (gradually tightening of emission limit values) has had an observable impact on the diffusion of new technology in the Finnish pulp and paper industry, particularly with respect to end-of-pipe technology.

Results from a survey by Becker and Englmann (2005) suggest that chemical industry's reactions to environmental regulations seem to be by far the most important reason for carrying out both end-of-pipe and production-integrated innovations.

Popp (2006) examined the innovation and diffusion of air pollution equipment, using patent data. He concludes that investors respond to domestic, but not to foreign regulatory pressures. His results suggest that transfers of environmental technologies across borders will be slowed by the need for domestic R&D to adapt these technologies to local markets.

Environmental policies can also have a *counterproductive* impact on innovations in environmental technology, especially if they are ill-designed. For example, Strasser (1997) argues that traditional environmental regulation has often discouraged innovation and diffusion of cleaner technology. He states that the extent to which a business is likely to develop or embrace new technologies in response to regulatory stimuli is a reasonably knowable and predictable process, and therefore regulators can craft environmental policies that will be consciously supportive of environmental technology. A change in regulatory culture is needed, as well as a multimedia and sector-oriented approach.

A familiar type of the possible 'anti-innovation' impact of environmental policy is the so-called 'new source bias', which results from regulations which impose stricter demands on new sources than on existing sources (see e.g. Stanton, 1993).

3.2 Evidence from the case studies

In the chemicals substitution case, it was concluded that public policy is a major driver to bring about environmentally benign innovations in the production and use of chemicals. Moreover, the available evidence does not reveal a conflict between stringent environmental requirements (including mandatory substitution of hazardous chemicals) and the rate of innovation in the chemical industry. There are even indications that in countries pursuing an active environmentally motivated substitution policy (Sweden, Denmark) the innovation activity in the chemical industry is higher than elsewhere. Obviously, however, the nature and direction of innovation will be affected as companies are confronted with the need to search for creative solutions to reduce the use of harmful chemicals.

The office appliances case provides an example where an environmentally beneficial innovation (*in casu* energy efficiency improvement) is at least partially motivated by product functionality (avoiding excessive heat). However, this case also strongly suggests that without public policy the considerable efficiency improvements would not have been achieved.

Environmental policy appeared to be one of the major drivers of innovation in the car fuel economy case (besides consumer demand and international competition). In the pulp and paper case, environmental policy turned out to be one driver of innovation among several others (including competition, cost considerations, consumer demand and NGO pressure).

4. Policy instruments and their specific roles

4.1 Literature findings

Generally, three broad categories of environmental policy instruments are distinguished:

- Direct regulation (or 'command-and-control'), which includes all kinds of instruments that impose legal obligations or prohibitions. This category includes for example bans, product and performance standards, emission limits, and permit conditions;
- Economic (or 'market based') instruments, covering instruments that use the price mechanism and financial incentives to encourage more environmentally-friendly behaviour. Examples are ecotaxes, emission charges, tradable permits, tax reductions and subsidies. Liability and compensation schemes (for environmental damage) and 'green' public procurement can also be seen als economic instruments;
- 'Voluntary' or 'communicative' instruments. This is in fact a residual group, covering a variety of instruments such as negotiated agreements, environmental management systems and information provision (including education and all kinds of labelling systems). In general, these instruments aim at facilitating environmentally benign actions rather than making them mandatory or financially attractive.

There is no unanimity in the literature about the question what kind of policy instruments is best suited to support the development and diffusion of environmental technology. Some general observations, however, can be made.

Direct regulation

Direct regulation (or 'command-and-control') instruments are often said to provide little incentives to look for 'greener' solutions once the standards or obligations are met. Nevertheless, direct regulation can play a positive role in inducing environmental innovation under certain conditions. For example, it was shown to work well in Germany when applying air emissions standards to power plant when the energy sector was still not liberalised and the energy companies had the possibility of passing through the costs. The context was important in having parties accept the required command and control. Evidence suggests that German emissions fell very quickly due to the instrument and context and faster than in countries where economic instruments were used (see e.g. Harrington *et al.*, 2004). This gives one counter example to the oft quoted position that market based instruments are more effective.

Direct regulation may also be a powerful instrument in spurring eco-innovation (provided that the standards set are tight and challenging) because firms may have an interest in developing cleaner technology if they can expect that that technology will become the basis for a future standard (e.g. BAT), so that they can sell it on the market.

Ashford (2005) argues that a 'command-and-control' type of environmental policy is needed to achieve the necessary improvements in eco- and energy efficiency. According to Ashford, the 'ecological modernization' approach, with its emphasis on cooperation and dialogue, will not be sufficient.

It is sometimes argued that direct regulation would favour 'end-of-pipe' solutions whereas economic instruments would be more conducive to process-integrated technology or 'cleaner production'. However, this is probably only true for certain types of direct regulation, in which the use of a specific abatement technology is (*de facto*) prescribed (see e.g. Frondel *et al.*, 2004) However, it is now common practice for environmental authorities to formulate permit conditions in terms of objectives that have to be met (e.g. emission limit values) and leaving the choice of technology to the firm.[5]

Economic instruments

Economic instruments are often seen as superior to direct regulation, because they provide (if designed properly) an additional and lasting financial incentive to look for 'greener' solutions. The available literature contains some support for this vision. For example, Jaffe *et al.* (2002) conclude that "the empirical evidence is generally consistent with theoretical findings that market-based instruments for environmental protection are likely to have significantly greater, positive impacts over time than command-and-control approaches on the invention, innovation and diffusion of desirable, environmentally-friendly technologies." Requate (2005), in a survey and discussion of recent developments on the incentives provided by environmental policy instruments for both adoption and development of advanced abatement technology, concludes that under competitive conditions market based instruments usually perform better than command and control. Moreover, taxes may provide stronger long term incentives than tradable permits if the regulator is myopic. Johnstone (2005) also presents some arguments from literature suggesting that taxes are more favourable to environmental innovations than tradable permits.

Economic instruments may be less appropriate if the main factor blocking eco-innovation is not a financial one. For instance, simulations with the MEI Energy Model (Elzenga and Ros, 2004), which also takes non-economic factors into account, suggest that voluntary agreements and regulations may be more effective than financial instruments (such as charges and subsidies) in stimulating the implementation of energy saving measures with a short payback period.

Positive financial incentives for eco-innovation, such as subsidies, have their proponents in literature as well. Some authors, such as Anderson *et al.* (2001) stress that 'standard' environmental policy instruments are not sufficient and that direct support for environment-oriented innovation is also needed. Main reasons for this are the positive externalities of innovation and the long time lag between the implementation of a standard policy and the market penetration of a new technology.

'Voluntary' instruments

'Voluntary' instruments, such as the EMAS scheme, can have a positive influence on environmental innovations. Rennings *et al.* (2006) found a positive impact of the maturity of environmental management systems on environmental process innovations. For environmental product innovations, learning processes by environmental management systems appeared to have a positive impact.

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[5] This approach is also embedded in the IPPC Directive (96/61/EC).

Conclusion and general considerations

In short, economic instruments are powerful drivers of eco-innovation, but other instruments should not be discarded. The appropriateness of particular instruments (or instrument mixes) may depend on the purpose for which they are used (e.g. innovation or diffusion) and the specific context in which they are applied (see e.g. Kemp, 2000). An analysis of the specific factors determining innovation (barriers and drivers) may be helpful to arrive at a good selection of instruments (see ten Brink *et al.*, 2006).

Policy instruments are hardly ever used in isolation. Different instruments are usually applied in combination, with a view to reaping the benefits of each of them and to achieving synergies. However, the use of instrument mixes may also have unwanted impacts (e.g. through inconsistencies and contradictory signals). In the past, the interactions between instruments have been neglected in the literature (Sorrell and Sijm, 2003).

Furthermore, the *design* of an instrument may be at least as important as the instrument type. One type of instrument can produce widely different results when applied differently. The real design of environmental instruments is influenced by the policy process, and it may deviate considerably from the theoretical 'ideal type' of the instrument (see e.g. Hemmelskamp, 1997). And finally, policy stringency is generally more important than the choice of single policy instruments (Frondel *et al.*, 2004).

4.2 Evidence from the case studies

The PV case provides a good opportunity to compare the merits of three different types of policy instruments approaches as applied in Germany, the UK and Japan. The German 'feed-in tariff' guarantees sustained above-market payments for the still costly PV technologies, differentiated according to the year of the installation – the later a PV system has been installed the lower the guaranteed tariff. Thus, the German model combines both measures for encouraging the PV market formation (by creating long-term investment incentives) and PV technology innovation (by reducing the tariffs and creating price pressure). In the UK, no strong commitment to promote PV technology is visible and the Renewables Obligation policy does not differentiate between the technologies at different stages of development. As a result, the UK has arguably "missed the boat" in conventional solar PV. The Japanese quota approach allows suppliers to set differentiated targets in the Renewable Portfolio Standard, but they can divide the percentage as they want, meaning they can choose the cheapest source. This makes it effectively similar to the UK approach. However, much of Japan's PV development in the past has been driven by specific large programmes and R&D support. German PV policy in the last couple of years has been more successful in promoting market development, while the Japanese have managed to stimulate PV manufacturing (Germany being a major export market for Japanese PV technology).

The chemicals substitution case also indicated that instrument choice may affect the (cost-)effectiveness of the policy. Banning a substance while allowing exemptions will often be less cost-effective than a tax: with the former instrument, firms may put more effort in lobbying for an exemption than in finding substitutes, whereas a tax ensures that a chemical substance will continue to be applied only in applications for which a substitute does not exist or is prohibitively expensive. But even if the policymaker prefers direct regulation, differences in instrument design can lead to quite different results. Obligations for a firm to meet certain emission or exposure standards or to search for alternatives may be at least as effective in terms of achieving substitution as an outright ban (with exemptions) on the hazardous substance. The case study thus supports the statement that it is not only the choice of the instrument, but also its design and implementation that determines its influence on innovative activity.

In the office appliances case, the power of public purchasing as an environmental policy instrument stimulating 'lead markets' was demonstrated convincingly. In particular, the American and Japanese obligations for public purchasers to buy energy efficient models ('Energy Star' and 'Top Runner' compliant respectively) have contributed to rapid market transformations. However, the case also showed the importance of updating the procurement standards at the right time and the right level, so as to avoid a situation where almost 100% of the market complies (rendering the instrument ineffective), while at the same time allowing for some competition (avoiding monopolies). Furthermore, this case study revealed that the potential of green public procurement in Europe is still only partly used, with large differences between Member States.

The case of car fuel economy shows that standards (such as the US CAFE standards) may not be very effective in stimulating innovation, especially if they lack ambition. *Technology forcing* standards (effectiveley requiring the use of a technology that is not yet available on the market) could be more effective, but a technology-forcing strategy is uncertain, with no guarantees of technological breakthroughs and extremely vulnerable to pressures from many different stakeholders and to unforeseen consequences. A successful technology forcing strategy could build on one or more existing technologies that have not yet been proven (commercially) in the area of application. The Japanese 'Top Runner' standards are not really technology forcing, but they contain a dynamic incentive in the sense that today's best products set the standard for tomorrow. The importance of instrument design is once again illustrated by the car fuel economy case: both the USA's and the Japanese standards differentiate by car type and size, making the outcome sensitive to shifts in consumer demand (e.g. towards larger and heavier cars). Similar problems can be observed in the EU approach (voluntary agreements with industry): consumer demand for heavier cars tends to frustrate the set objective (and in addition, the industry association cannot impose the objectives on its individual members).

The pulp and paper case suggests that, in practice, the type of policy instrument (economic, command-and-control) that is applied matters less, but that it is other characteristics of the instruments (intensity, flexibility, dynamic orientation) that matter more. Clear, consistent and credible targets are essential, especially in a capital intensive industry (such as pulp and paper) with long term investments in production capacity.

5. Conclusions and policy implications

5.1 Environmental policy's role in innovation: driving, steering or braking?

The literature and cases that have been studied in this project strongly suggest that, in general, environmental policy does not have a negative influence on the level of innovation in industry. On the other hand, there is not much evidence for the opposite conclusion (that environmental policy would be a major engine behind technological innovation, making industry investing more in R&D than they would otherwise do).[6] It seems safe to say that environmental policy's role in innovation is a steering one, rather than braking or driving. In this role, it is only one among many other factors determining the direction of industry's innovation efforts. The relative importance of this role differs from case to case.

Those other factors may or may not steer the innovation process in the same direction as the environmental policy maker has in mind. Synergies and 'autonomous' trends towards cleaner technology do occur, but are by no means guaranteed. Innovation-oriented environmental policy will therefore remain essential for sustainable technological development. Such a policy addresses two kinds of externalities simultaneously: the negative externality of pollution (and other environmental damage) and the positive externality of R&D (spillovers).

Inducing innovation requires strong policy: the objectives and instruments should make it clear that significant changes are needed. Weak policy, whether in terms of weak standards (e.g. car fuel economy standards in the USA), or insufficient financial incentives (e.g. solar PV support in the UK) will not be likely to achieve it.

Obviously, with markets becoming increasingly globalised, there is no guarantee that the innovations induced by European environmental policy will be developed by European industry itself (a point illustrated by the PV case). However, even the introduction of 'imported' new technology implies an innovative activity. Moreover, there are several examples of domestic innovations (developed in response to environmental policy) that became successful export items as a result of similar policies implemented abroad (see for instance the examples of Germany in the chemicals substitution case and Japan in the office appliances case).

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[6] Obviously, it is conceivable that certain types of innovation could be stifled by environmental policy – e.g. banning a substance because of some rather marginal environmental benefit might squelch a whole new application that could have been important, or the money for the environmental innovation could have been invested elsewhere to greater effect. Additional research might reveal the existence and relative importance of such cases, although it is of course always problematic to search for 'evidence by absence'.

5.2 Instrument choice and instrument design

It is widely acknowledged (and to some extent confirmed by this study) that economic instruments have some superior features in stimulating environmental innovations. However. the choice of appropriate policy instruments will also be determined by the nature of the technological innovation that is aimed at. Obviously, radical innovations (involving major breakthroughs and systemic changes) require a different set of instruments than incremental innovations. Similarly, product, process and organisational innovations each call for a different kind of policy approach.

The effectiveness of a policy instrument will furthermore at least partly depend on the stage of the innovation process. For example, Figure 5.1, taken from IEA (2000b), shows

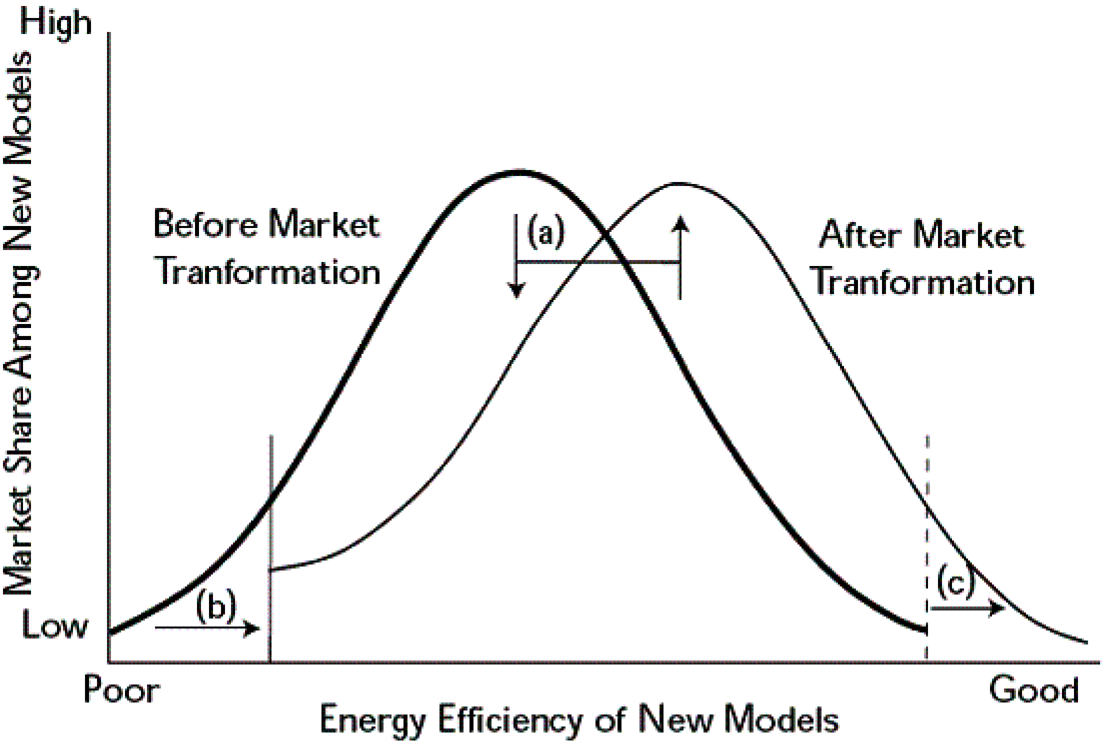

Figure 5.1 Impact of several market transformation instruments on the dissemination of energy efficient equipment (Source: IEA, 2000b).

the possible role of different policy instruments in the process of market transformation towards more energy efficient equipment:

(a) Labels, fiscal incentives and other customer focus instruments increase the average efficiency of the market, increasing the market shares of efficient models at the expense of inefficient ones. Also, fleet average standards and voluntary programmes encourage manufacturers to increase the average efficiency of their product lines;

(b) Minimum efficiency standards prevent the marketing of low-efficiency appliances. This process is facilitated on markets where labels have already reduced the market shares of the products;

(c) Support for innovation and research and development enable new, more efficient, products to be introduced to the market.

Obviously, Figure 5.1 is a stylised representation of the market profile. The relative sizes of the market transformations (a), (b) and (c) can vary considerably. The market transformations also have time and cost elements, which are not shown.

The relevance of innovation cycle stage for instrument choice was also addressed in a recent report on the Policy Pathways (POPA) project (ten Brink *et al.*, 2006). This report stresses, among others, the importance of R&D support in the earliest stage of the cycle. Public procurement and other economic incentives become important in the 'niche market' stage, whereas standards and labelling can play a role in more mature markets.

Table 5.1 provides a simplified synopsis of the instruments that could be applied under certain conditions relating to the type of innovation, the main factors (or barriers) and the stage in the innovation cycle.

Generally, the 'hard' type of instruments (regulatory and economic instruments) are the most effective ones to stimulate environmental innovation. These instruments (if designed and implemented appropriately) give the clearest signals about the direction and the magnitude of the environmental improvements that the innovations should produce.[7] 'Soft' instruments, such as education and information provision can play a complementary role in spreading knowledge and expertise and in creating markets for environmental innovations. Voluntary agreements will usually only be effective if there are no major barriers (meaning that the innovation would probably come about anyway), or if there is a credible threat of sanctions (e.g. regulations) in case of non-compliance. In practice, combinations of different instruments will often be used, implying that the impacts of interactions between them also need to be addressed. Furthermore, it goes without saying that any policy instrument will only be effective if accompanied by adequate monitoring and enforcement.

Instrument design is at least as important as instrument choice. Take the example of standards. They can be made mandatory (direct regulation), be used as a basis for tax reduction or public procurement (economic instruments) or be referred to in eco-labelling criteria or voluntary agreements ('soft' instruments). In principle, they can be effective in each of these instrument types, but the crucial question is of course how the standard is defined and at what level it is set. A careful balance has to be found between ambition and realism, so as to ensure that there are lasting incentives for innovation but also achievable opportunities and sufficient competition. Continuous improvements in best available techniques (BAT) [8] and other benchmarks could be realised by introducing obligations to look for new technological opportunities, even beyond the borders of the own industry. On the other hand, radical innovations may require strong direct support for emerging technologies (often developed outside the vested firms) that pose a challenge to the existing 'locked in' technology.

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[7] Nevertheless, innovation is an inherently uncertain process,.The exact impact of a policy instrument on technological progress can therefore never be predicted.

[8] As in the Integrated Pollution Prevention and Control Directive.

Table 5.1 Instruments, characteristics and context of the innovation

Instrument type	Type of innovation	Innovation factors/barriers	Stage in innovation process/cycle
Direct regulation			
Emission standards (mandatory)	Process	Technological opportunities exist, but lack of market demand	All*
Product standards (mandatory)	Product	Technological opportunities exist, but lack of market demand	All*
Economic instruments			
R&D support	Product and process	Lack of technological opportunities; lack of appropriability conditions; perceived risk	R&D stage
Public procurement	Product	Latent market demand, but barriers for massive uptake (e.g. risk, price)	Niche market / early adopters stage
Emission charges / tradable permits	Process	Technological opportunities may exist, but cost barrier to uptake; or they may not exist (then the economic incentive will stimulate searching for them)	All
Financial incentives stimulating market demand	Product	Latent market demand, but price/cost barrier	Niche market / early adopters stage
Information and communication			
(Eco-)labelling	Product	Latent market demand, but information barrier	Early adopters / mature market stage
Voluntary agreements	Product and process	Various	All
No public intervention			
None (market can do the job on its own)	Product and process	No barriers	All

* Standards can already play a role in an early stage, as illustrated by the Japanese 'Top Runner' programme where today's best performing products set the standard for tomorrow.

5.3 Implications for impact assessment

In its most recent Impact Assessment Guidelines[9] the European Commission has included 'innovation and research' as a separate item to be assessed under 'economic impacts'. The question then arises: how can these impacts be identified in the case of new environmental policy proposals?

On the basis of the findings of this project, it is impossible to provide a standard answer to this question. Innovation is an inherently unpredictable process, in which chance, coincidence and serendipity tend to play major roles. Nevertheless, we can make a few re-

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marks concerning the 'key questions' to be addressed (as formulated in Table 1 of the Impact Assessment Guidelines)[10]:

Does the option stimulate or hinder research and development?
As noted before, environmental policy will in general not be an obstacle to research and development. A policy option's chance of stimulating R&D is likely to be greater if it provides a clear, consistent and lasting incentive to develop and adopt innovative solutions. It should be challenging and feasible at the same time.

Does it facilitate the introduction and dissemination of new production methods, technologies and products?
Generally, this question can probably be answered affirmatively for major new environmental policy initiatives. The extent to which this is the case depends on the choice and design of the policy instrument(s). For instance, the positive impact will be stronger if the policy succeeds in avoiding the 'new source bias' (i.e. it should preferably not impose more stringent requirements on newcomers than on incumbents).

Does it affect intellectual property rights?
The present study has not produced any evidence for this kind of impacts from environmental policies.

Does it promote or limit academic or industrial research?
The answer to this question will be basically the same as to the first question on R&D in general.

Does it promote greater resource efficiency?
Given the fact that a substantial part of environmental policy has the explicit aim of improving resource efficiency, a positive answer can be expected as a rule.

5.4 Final remarks

Environmental policies should be developed with the primary objective of addressing environmental objectives and not as a direct mechanism focused on encouraging innovation. That said, it is also obvious that solving environmental problems calls for innovative solutions which sometimes may, but more often may not be brought about by the market alone. Carefully designed, innovation-friendly types of environmental policy are therefore indispensable. These policies should be judged by their (cost-)effectiveness in terms of environmental improvement and eco-innovation. Their (positive or negative) impacts on levels of innovation in general, competitiveness, economic growth and employment are not likely to be substantial and should in any case be regarded as secondary corrolaries (see also IMV, 2006).

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10 Obviously, many more issues have to be addressed in an impact assessment, but the present study focuses on innovation aspects.

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Appendix I. Summaries of case studies

Case Study 1: Car fuel economy / CO_2 emissions[11]

The technology

This case study investigates the policy instruments which have been implemented in order to promote fuel efficiency in passenger cars. A number of specific technological developments are identified as contributing to the observed emission reductions. For petrol cars the improved fuel efficiency was primarily due to a shift from singlepoint injection to multipoint injection. In diesel cars the improvement in fuel efficiency was attributed to the almost complete penetration of the direct injection/high pressure technology over the period 1995 to 2003. Comparably, the share of direct injection in petrol cars is still very low. As noted below however, the levels of innovation in the USA have been substantially lower and these technological developments have therefore been less widely introduced.

What type(s) of policies were assessed?

Three area experiences of attempts to improve fuel efficiency in cars are addressed by the case study.

Firstly the European experience is focused on. One important element of Europe's strategy to reduce CO_2 emissions from passenger cars and to improve fuel efficiency are the voluntary agreements that were brokered with the automobile industry to reduce total new passenger fleet average CO_2 emissions according to specific targets and timetables.[12] The voluntary agreements were concluded in 1998 with the European Automobile Manufacturers' Association (ACEA), the Japan Automobile Manufacturers Association (JAMA), and the Korea Automobile Manufacturers Association (KAMA). The agreements are collectively labelled as the ACEA Agreement. The target for new passenger fleet average CO_2 emissions is 140 g CO_2/km by 2008/9.[13] The Community's target for 2012 is 120 g CO_2/km. This longer-term target has not yet been included in any formal agreement with the car industry. The Commission has stated on several occasions that a failure of the car industry to meet the 2008/9 target might lead to mandatory regulation in the future.

Secondly the United States (US) Corporate Average Fuel Economy (CAFE) programme is studied. In 1975 the CAFE programme was initiated by US Congress as a measure to conserve petrol and to reduce US reliance on imported oil (Gerard and Lave, 2003). The CAFE standards set mandatory average fuel economy standards for car manufacturers for passenger cars and light-duty trucks. For passenger cars, the standards increased from

[11] See Kuik (2006a) for the full case study report.

[12] Other elements include fuel-economy labelling on cars, and the promotion of car fuel efficiency by fiscal measures (EC, 2005).

[13] The target year is 2008 for ACEA and 2009 for JAMA and KAMA.

18 miles per gallon (mpg) in 1978 to 27.5 mpg in 1985. For light-duty trucks, the standard is 20.7 mpg. These standards have not been raised since 1985.

Thirdly, the Japanese Top Runner Programme is investigated. The Top Runner Programme was introduced in Japan in 1999 as part of the revision of the Law on the Rational Use of Energy, addressing many sectors, including the car manufacturing sector (Naturvårdsverket, 2005). Among the targeted product groups (e.g. passenger cars), the most energy-efficient product (the "Top Runner") becomes the basis of the regulatory standard in 3 to 12 years time, taking into account the potential for technological innovation and diffusion. The standards in the Top Runner Program are also used in the green purchasing law and the green car tax scheme. Additionally, there is an annual award for the most energy-efficient products and systems.

Historical development, observed stages of innovation, market penetration

It is evident from the case study that there has been a marked difference between the case study areas in the levels of historical development and resulting market penetration of innovative fuel-efficient engine technologies.

Under the ACEA agreement largely a trend of diffusion rather than breakthrough innovation has occurred in the car manufacturing sector. For example, in 1995 only Volkswagen and Audi offered versions of a Turbo Diesel Injection (TDI) engine, whereas today such engine technology is widely available. Also, multipoint injection in petrol cars and direct injection/high pressure technology in diesel cars, has been developed and diffused to penetrate the marketplace.

Compared to the European targets, the CAFE standards are not very ambitious. The 140 g CO_2/km target from the ACEA Agreement translates into a fuel economy standard of 5.9 ℓ/100 km. The US CAFE standard for petrol passenger cars is equivalent to 9 ℓ/100 km and the light-duty truck standards for minivans, pickups and sport utility vehicles are even less ambitious. Due to such unambitious targets being set under this policy regime, innovation in the US has been much lower since targets for fuel economy have not been raised since 1985. The small amount of technology push or market pull forces, has resulted in a lack of market penetration of innovative fuel efficiency technology. Indeed the average fuel economy of new cars in the US has not improved since the mid 1980's.

The experience with the Top Runner Program has been good. It is expected that car manufaturers will manage to meet the Top Runner standards prior to the target year. As explained above, the Top Runner Program provides for dynamic, and therefore ambitious standards

Observed learning curves and economies of scale

The case study concluded that, as yet, no learning curves for CO_2 reduction measures in cars have been estimated. However, previous emissions reduction measures for conventional air pollutants have shown learning rates of approximately thirty percent in the United States.

Policy influence on innovation

The ACEA program in Europe and the Top Runner program in Japan are clearly more ambitious in their targets for innovation than the CAFE program in the US. A further difference is that the Japanese and US programs are mandatory, while the EU program is voluntary (although with the threat of regulation if EU targets are not met).

The EU and Japanese policy instruments have more effect on innovation (in scope and speed) than the US CAFE program. This is not surprising, given the large gap between the stringency of fuel-efficiency standards in Europe and Japan versus the US. None of the standards, however, are expected to give incentives for radical or break-through innovations. Both ACEA and the Top Runner Programme seem to be focussing more on the rapid diffusion of already available technologies and incremental innovations. To date, however, the ACEA agreement has not been very successful in stimulating promising newer technologies such as direct injection in petrol cars and the production of hybrid cars.

It is not yet clear whether there is a discernable difference between mandatory or voluntary types of policy instruments and their respective effects. Further, it is not yet known whether the car industry will meet the final ACEA standards in 2008, or how the European Commission will react if the targets are not met. The US CAFE program has mandatory standards, but it also has legal loopholes and according to some observers the non-compliance penalties are too small to make a big impression on car manufacturers.

One interesting distinction between the European ACEA approach and the Japanese Top Runner approach is that ACEA sets standards at the industry level, while the Top Runner Programme sets standards at the company level. Perhaps this latter approach has the advantage that companies are more directly involved in the process. It is, for example, remarkable that only half of the European car manufacturers mentioned the ACEA standard in their annual reports (WRI, 2005).

Case Study 2: Energy efficiency of electr(on)ic appliances[14]

The technology

This case study investigates the policy instruments which have been implemented in order to promote efficiency improvements in electronic (mainly office) appliances. These appliances are referred to as Information and Communication Technology (ICT). Over the past decade, concern has been expressed about the rapidly growing energy use by personal computers (PCs) and other electronic office appliances. Previous estimates regarding the amount of energy used by such devices have ranged from 2% to 13% of the total (US domestic) electricity demand. Nonetheless, it is clear that the increase in the numbers of ICT appliances has been accompanied by a decrease in their specific energy use. For example, over the past two decades the performance of the PC has increased over 400 fold, while the energy consumed by the system is largely unchanged. A primary reason for the relatively low power usage of ICT products can be attributed to the

[14] See Oosterhuis (2006a) for the full case study report.

introduction of technologies that ‘manage’ the power consumption of these devices (Intel, 2002).

What type(s) of policies were assessed?

Three area experiences of attempts to improve ICT energy efficiency are addressed by the case study, with an emphasis on public procurement.

Firstly the European experience is focused on. The EU supports the use of energy efficiency criteria in public tenders. However, it has not yet made such procurement practices mandatory. For example, the recent Directive on energy end-use efficiency and energy services (2006/32/EC) includes an article (5) obliging Member States to ‘*ensure that energy efficiency improvement measures are taken by the public sector, focussing on cost-effective measures which generate the largest energy savings in the shortest span of time*.’ They should use at least two out of a list of six measures (set out in Annex VI of the Directive), one of which is the requirement ‘*to purchase equipment that has efficient energy consumption in all modes, including in standby mode, using, where applicable, minimised life-cycle cost analysis or comparable methods to ensure cost-effectiveness*.’ In other words, there is no obligation to require the procurement of energy efficient office equipment if other measures are considered to be more cost-effective. Nevertheless, the option of mandatory public procurement is still being discussed.

Secondly the American ICT energy efficiency programme is addressed. This is a case of an extremely simple use of centralised powers. In 1993, President Clinton signed Executive Order 12845 requiring Federal agencies to purchase computer equipment, specifically personal computers, monitors and printers that met the Energy Star requirements. Largely due to this, as we shall see below, Energy Star labelled products soon came to dominate the market.

Thirdly, the Japanese Green Procurement Law and Top Runner Programmes are studied. Both of these programmes are mandatory. Japan can be considered to be the international leader in green purchasing of office equipment and electronics. Führ (2001) considers this to be one reason for the advanced position Japanese electronics companies have, even on other markets, when it comes to environmental compliance. In 2001 the Law concerning the Promotion of Public Green Procurement (Green Procurement Law) came into force. As far as energy efficiency criteria are concerned, the Green Procurement Law incorporates the standards developed in the Top Runner Program. Under the Japanese Top Runner Programme energy efficiency standards are formulated for various product groups, including copiers and computers. These standards have to be met within 3 to 12 years, depending on the product group, and they are based upon the most energy-efficient model on the current market: “today’s best model sets tomorrow’s standards” (IEA, 2003). There are currently 12 ICT product groups included in both the Top Runner Programme and the Green Procurement Law.

Historical development, stages of innovation, market penetration

The first widely used power management technology for PCs, advanced power management (APM), was introduced in the beginning of the 1990s. Intel, Microsoft and other leading IT manufacturers worked jointly to enable hardware and software interaction, resulting in power managed PCs. Since this time, many innovative additions and revisions to this technology have occurred. Another important trend leading to improved energy efficiency of PCs has been the shift from traditional cathode ray tube (CRT) monitors towards the more efficient flat screen monitors.

For other products, such as photocopiers, energy efficiency improvements also have been achieved by reducing energy use during the time when the appliance is not in use. In the case of conventional copiers, more than 90% of the energy is consumed when they are not being used. Energy consumption can be decreased by reducing the amount of energy required to heat the roller (that applies the toner to the paper). Reducing warm-up times can take away the need to maintain the roller at a high temperature during the whole day. Copiers from Ricoh and Canon received the IEA DSM Award of Excellence. Both copiers consume 70-75% less energy than comparable copiers on the market and use new technologies to reduce warm-up times.[15]

PCs and other electronic office appliances have relatively short lifetimes and the frequency of replacement is therefore high. This implies that a rapid market penetration of innovative energy efficient models will soon be reflected in the overall ICT stock in use. The rapid market penetration of energy efficient office appliances can be observed in Europe. In its Communication on the implementation of the Energy Star programme in Europe (COM(2006) 140 final) the European Commission concluded that to date the Energy Star technical specifications are being fulfilled by almost all the models of the five companies that had submitted data.

Observed learning curves and economies of scale

In theoretical terms the case study outlines the rationale for public green procurement plans, and the resultant effect that can be had on the targeted market. It is argued that if such green public procurement plans are used, the cumulative volume of sales to public purchasers would imply a movement towards the right hand side of the 'learning curve'. The new product will benefit from economies of scale and learning effects, and prices will tend to decrease. This will in turn make the low-energy appliance more attractive for buyers in the private sphere. In this way the government can act as a 'launching customer' and initiate market transformation.

The case study investigation identifies how both the US and Japanese public policies instigated a progression along the learning curves, allowing for new processes to be invested in and consequently economies of scale to be exploited.

Policy influence on innovation

In the European case, it seems that the policy for encouraging innovation in energy efficiency of ICT has been incoherently applied in the past. Due to a non mandatory approach which has been employed, it can be said that out of the three territories which were investigated, it is the European approach which has inspired the least amount of innovation in energy efficient ICT.

Experience from the US shows that Executive Order 12845 has been extremely influential in encouraging innovation in the ICT sector. The measure was taken in an early stage

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[15] Source: IEA DSM website (http://dsm.iea.org/NewDSM/awards.asp, accessed 7 June 2006).

of the innovation process: the first Energy Star labelled products had been introduced on the market in the preceding year (1992). As a direct result of the Order, it is estimated that in 1999 95% of monitors, 85% of computers and 99% of printers sold were Energy Star compliant (Webber et al., 2000). According to Siemens (2001), the Executive Order was crucial in creating awareness and the public market for Energy Star products, particularly office equipment. Moreover, extensive promotion efforts to all government levels, tools to demonstrate cost and greenhouse gas emission savings, and integration within government procurement catalogues, appear also to have been key to promoting Energy Star procurement.

The Japanese policy approach was also highly successful. Until 2004, computers were included in the Green Procurement Law. The success of the policy approach has been illustrated by the fact that as all of the computers in the market have met the set energy efficiency criteria, they have been collectively taken off the list of green procurement items. With the introduction of new Top Runner standards however, computers will be reintroduced in the Green Procurement Law again, in order to improve energy efficiency gains further.

The fact that Energy Star labelled office appliances have also come to dominate the European market (despite the absence of mandatory procurement in Europe) can be explained by the global nature of the market. Once the market penetration had been triggered and enhanced by the policies in the USA and Japan, the energy efficient innovation could easily spread to other parts of the world.

An interesting component of the case study is the questionnaire which was undertaken in order to solicit the views of experts in the area, and obtain additional information on the perceived effectiveness of public policy instruments on innovation in ICT. The study found that the experts appeared to have divergent opinions on the importance of public policy for the development and diffusion of energy efficient innovations. Some emphasised the overriding importance of global market demand and the general concern about energy issues and climate change. Others pointed to the important role of public institutions as purchasers of office appliances and to the use of the Energy Star in public procurement, providing a strong incentive to improve energy efficiency. This was reflected in the ranking of policy instruments' effectiveness, where a great deal of unanimity exists among respondents. Mandatory public procurement of energy efficient equipment is generally seen as the most (or second most) effective instrument. Mandatory energy performance standards also obtained a high ranking with the experts.

Case Study 3: Photovoltaics (PV)[16]

The technology

Photovoltaic (PV) cells produce electricity directly when exposed to sunlight. This property has made them invaluable in applications where other sources of energy are hard to access, such as their original use in satellites, but also in remote applications like telecommunications repeater stations and off-grid homes. Given the abundance and free availability of sunlight, expanding into much broader use has long been an attractive

[16] See Anderson *et al.* (2006) for the full case study report.

prospect. However, there are technical challenges to overcome in bringing costs down to the point where this is feasible at a large scale compared to the provision of electricity from traditional sources.

What type(s) of policies were assessed?

The main policies associated with solar PV support are given an overview before the case study addresses Germany, the UK and Japan PV markets. The major policy instruments for promotion in each of the respective nations are identified. The nature and chronology of the instruments are set out in Tables I.1 – I.3:

Table I.1 German PV Policy Chronology.

Policy	**Operating principle**	**Year of implementation**
1.000 roofs	Investment subsidy of 70% of costs with upper cap	1991-1995
Electricity Feed-in Law (Budget 3.5 M EUR paid by final customer)	Feed-in tariffs (90% of the average price for end consumer)	1991-03.2000
Cost covering feed-in tariffs from utilities and local communities	Feed-in tariffs of up to 1.12 EUR/kWh fixed for 20 years	1996-1999
Green tariffs from utilities as voluntary participation for the customers	Higher feed-in tariffs paid to realise new PV plants	1996-1999
Market stimulation programme	Investment subsidies on schools, churches and congregations	1999-2001 (on schools still ongoing)
100.000 roofs (Subsidy of 695 M EUR)	Soft loan: 10 years duration, 2 years free of redemption	1999-ongoing
Renewable Energy Act (Budget 83 M EUR paid by final customer)	Feed-in tariff of €0.457 fixed for 20 years (5% decrease annually for later installation from 2002 on)	01.04.2000-ongoing
Promotion of research projects in the field of PV	Financial support for joint projects by research and industry entities	2004-ongoing

Table I.2 Japanese PV Policy Chronology.

Policy	Operating principle	Year of implementation
Sunshine Project	Promotion of research activities aiming at development of technologies from alternative energy	1974 - 1994
New Sunshine project	Successor of the aforementioned project, integrating the Sunshine, the Moonlight (Energy-saving technology R & D) and the Global Environment Technology Projects aiming at accelerating the market penetration of the technologies	1993 -2000
Projects for New Energies	(1) *Seed identification* – related to production technologies, industrialisation and commercialisation (up to 50% funding) (2) *Advanced PV Generation* - 100% sponsored development of pilot plants for new PV technologies	2001
Monitoring programme for residential PV systems	Aimed at stimulation of the PV market.; 50% of PV installation costs were subsidised	1994-1996
Programme for the development of the infrastructure for the introduction of residental PV systems	Successor of the aforementioned programme with substantially increased funding facilities.	1997
PV Field Test Project for Industrial Use	Subsidy (50%) for private companies, local public organisations for installation of PV systems	1998
Subsidy programmes of local governments	Funding of up to 40% of the installation costs	
Renewable portfolio standard (RPS)	Legislation aiming at achieving a ratio of 3.2% for the renewable energy in the total energy supply till 2010. It requires each power retailer to set an annual sales target for six types of renewable energy (including PV)	1st April 2003

Table I.3 UK PV Policy Chronology.

Policy	Operating principle	Year of implementation
Major Photovoltaics Demonstration Programme (PVMDP) (worth £31 million (DTI 2004))	Grants between 40% and 50% are paid for installation of solar electricity panels. These are available to householders, business or social housing groups.	2002-March 2006
Low Carbon Buildings Programme (worth £80 million (EST 2006))	This programme supersedes the aforementioned one, with the support of PV installations being a substantial part of it.	April 2006
Renewables Obligation	The Obligation requires suppliers to source an annually increasing percentage (5.5% for 2005/06) of their sales from renewables. For each megawatt hour of renewable energy generated, a tradable certificate called a Renewables Obligation Certificate (ROC) is issued.	2002
Financial incentives	Climate change levy exemption for PV	2001

Historical development, stages of innovation, market penetration

There are two main types of crystalline silicon used in PV: mono-crystalline and poly-crystalline. Between them they represent 93% of the solar market (Solarbuzz, 2006). In the former case, silicon wafers are sliced from solid ingots, an expensive process that leads to waste. Efficiency (meaning the amount of sunlight striking the cell that is converted to electricity) is highest in such cells however. Thus the story of PV technology development to date is largely one of finding cheaper manufacturing processes while maintaining useful efficiencies.

Therefore, the primary challenge associated with PV is the challenge of innovating to lower cost, with the associated factors being materials availability and costs; the potential for scale up of manufacturing; high enough efficiency to avoid needing too much surface area to be practical; durability, reliability, and stability. Aside from the solar cells themselves, costs are also significantly influenced by the required balance of systems (BoS) – the ancillary equipment such as the components needed for mounting, power storage, power conditioning and site-specific installation. As PV is scalable from a single cell to an array as large as desired, and can be either stand-alone (requiring storage) or grid-connected, the proportion of system price due to BoS is highly variable, but can be up to 50% of total costs. Technology development tends to be driven by progress in other fields – power conditioning equipment, for example, is not by any means dominated by the solar field (PV Resources, 2006).

In terms of market penetration, PV can be categorised as having three main applications. Firstly commercial products such a watches and calculators. Secondly, off grid types such as telecommunications, off grid domestic and off grid industrial/commercial applications. Thirdly types of on grid applications such as small grid connected domestic and central large scale grid connected arrays.

Japan and Germany lead the world in annual installations by a large margin. The global annual growth rate of PV from 1992 to 2001 was 29%. In 2002, Japan, Germany and the United States accounted for 92% of new installations. Over the period 1998-2002, annual growth rates in Japan were 48%, 52% in Germany and 21% in the USA. The nature of the systems shifted since 1990 – then, they tended to be solely off-grid homes, telecommunications and commercial uses; now the market is driven by small on-grid building integrated PV.

Observed learning curves and economies of scale

In the case of PV, learning is attributed to increases in module efficiencies, manufacturing experience and economies of scale. When examining the effect of learning on PV systems cost, though, it is useful to differentiate between PV modules and BoS. While PV modules are deeply related to PV experience, BoS are based mainly on mass-produced components, thus improvements are more the result of spill-over knowledge from other sectors. According to the learning curve theory, an increase by a fixed percentage of the cumulative production should lead to a percentage reduction in price. Figure I.3 represents the learning curve for PV in the world market between 1976 and 2002

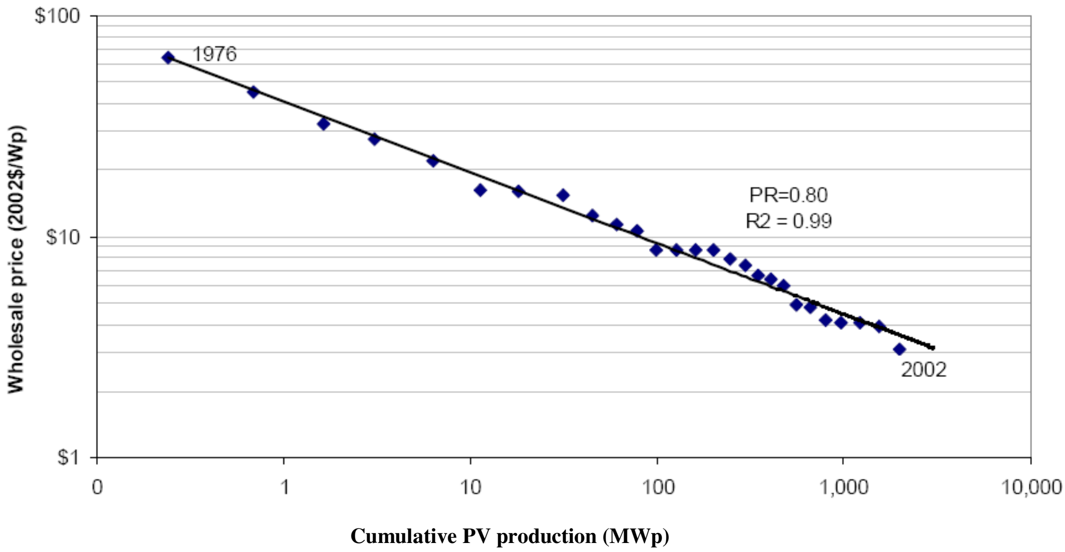

Figure I.1 Experience curve for PV (after Johnson, 2002 and Dunay, 2003).

The progress ratio (PR) gives the change in price corresponding to a doubling of the production volume. Data from 1976 to 2002 reveals a progress ratio of 80%, meaning that the price is reduced to 0.8 of its previous level after doubling cumulative sales. The fact that the progress ratio is the same for any part of the experience curve implies that young technologies learn faster from market experience than old technologies with the same progress ratios. In the case of PV, market expansion from 1 to 2 MW reduced prices by 20% when the technology was first introduced, but at a later stage production had to grow faster to have the same price reduction, e.g. from 100 to 200 MW.

Policy influence on innovation

In the German case, the introduced policy measures have yielded increases in the innovation, production and application of PV technology in Germany. In 2004 Germany became the world leader in terms of the yearly installed PV. Furthermore, a drop in prices for PV systems in Germany of almost 40% has been observed since 1995. At one point, aggressive government incentive programmes led to tightening supply, despite expanding manufacturing, and 2000 and 2001 prices were higher than in 1999 (Duke, 2003). Recognising the attractiveness of the German market, foreign competition increased, leading to a significant price fall in 2003 (BMU, 2003).

In the Japanese case policy aimed at inducing innovation in the PV sector seems also to have been successful. Much of Japan's PV development to date has been driven by specific large programmes such as the solar roofs initiative. In contrast their recent RPS initiative is not expected to yield historical levels of PV deployment (as the RPS aims at raising the proportion of energy from renewables for electricity generation to only 1.35% by 2010, much less than Europe's 12%).

Lastly in the UK case, policy support for either innovation or diffusion of PV has been relatively weak. The implemented Renewables Obligation has done little to promote PV development as it does not differentiate between the technologies at different stages of development, and tends to promote those closest to the market (i.e. not PV). Deployment levels have also been relatively small through other subsidy schemes. The Carbon Trust (2003) have stated that the UK has arguably "missed the boat" in developing conventional PV systems.

In comparing Germany, the UK and Japan in the above context, lessons emerge. The feed-in tariff's main advantage is that it guarantees sustained above-market payments for the still costly PV technologies – the guaranteed feed-in tariffs for the electricity from PV in Germany are considerably higher than for the other technologies (50.62 cents/kWh for electricity from PV as opposed to 8.7 cents/kWh for wind energy).

The UK policy approach of using the Renewables Obligation and exemptions from the climate change levy, have been more expensive and less effective than other policy mechanisms (such as those in Germany, Luxembourg and Austria).

Case Study 4: Emissions from pulp and paper production[17]

The technology

Pulp and paper is a mature industry. Industrialised paper manufacturing in Europe started in the early 19th century (Berkhout, 2005). It is a capital and resource-intensive industry that contributes to many environmental problems, including global warming, human toxicity, eco-toxicity, photochemical oxidation, acidification, nutrification, and solid wastes (Blazejczak and Edler, 2000).

Paper is made of natural fibres, either from wood or from recycled materials. Figure I.2 below presents a schematic representation of the production system. The harvested wood is first processed so that the fibres are separated from the unusable fraction of the wood, the lignin. Pulp making can be done mechanically of chemically. The pulp is then bleached and further processed, depending on the type and grade of paper that is to be produced. In the paper factory, the pulp is dried and pressed to produce paper sheets. Post-use, an increasing percentage of paper and paper products are recycled in Europe, with waste pulp and paper residues being either landfilled or incinerated.

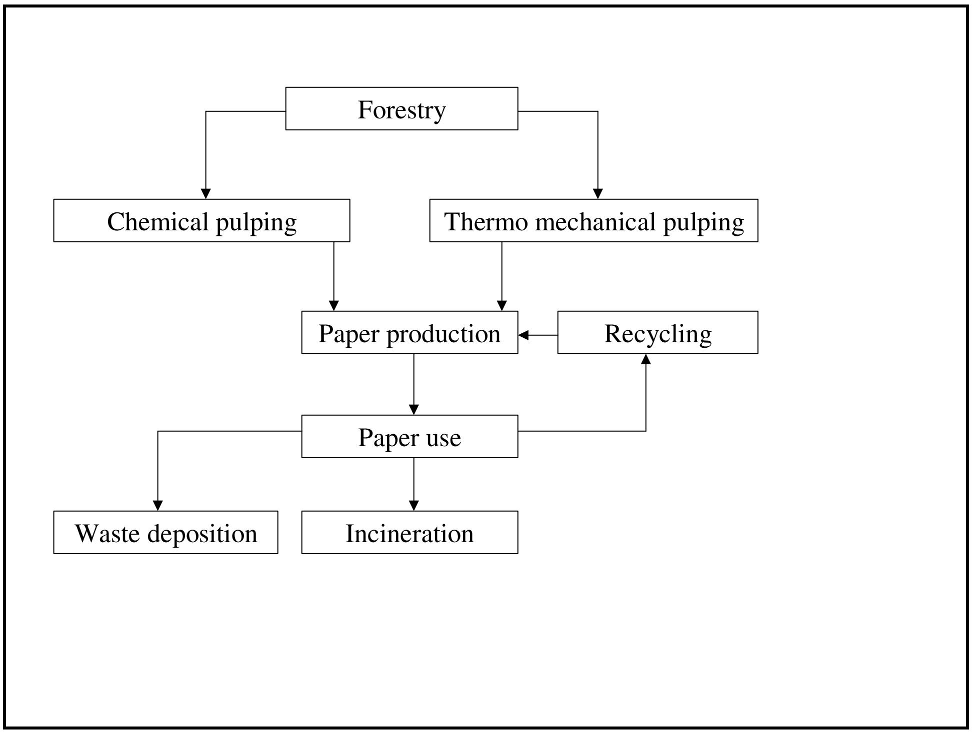

Figure I.2 Paper production system (from: Berkhout, 2005).

What type(s) of policies were assessed?

Rather than investigating policies on a country by country basis, the pulp and paper case study summarises previous research studies which focus on the impact of environmental

[17] See Kuik (2006b) for the full case study report.

policies on technological advances in a number of countries. The policy types include command-and-control, industry-wide targets and consumer awareness.

It was found that among large paper producing countries, Sweden is the most innovation-friendly regarding energy consumption in the pulp and paper industry and waste paper recycling. Swedish policy is characterised by a search for consensus in combination with ambitious long-term goals. Japan's policy with respect to the pulp and paper industry is considered to be less innovation-friendly, mainly because its pulp and paper industry is not considered to be a 'strategic' sector in industrial policy. Environmental policy in the United States is considered to be least innovation-friendly as it relies too much on particularly inflexible technology standards.

The paper industry in the Netherlands is confronted with all types of instruments. The Netherlands distinguishes between top-down instruments (command-and-control), economic instruments (taxes/subsidies), and interactive instruments. One of the interactive instruments used in the Netherlands is known as the Target Group Policy, where collective environmental targets for industry sectors are set through an interactive process between government and the industry associations. Once these collective targets are set, the industry association co-ordinates the abatement efforts of its members.

Apart from environmental policy instruments per se, 'green' consumer demand and pressure from environmental groups are also of interest in explaining innovation in the pulp and paper industry.

Historical development, stages of innovation, market penetration

The pulp and paper industry has undergone major changes in environmental performance in the last two decades which according to some observers, is quite surprising for an industry that is an example of a mature sector with a low rate of innovation (Reinstaller, 2005). The most spectacular changes in the recent decades have been a radical change in bleaching technology, that minimised the use of chlorine and greatly reduced or avoided altogether the emissions of dioxins, and the increase in the use of recycled paper as an input in the paper production process.

An important barrier to quick process changes has been the industry's slow capital-turnover rate. A survey in 1997/8 revealed that the median age of paper machines in Europe was 23 years (Berkhout, 2005). Product changes, such as the transition toward chlorine-free paper have been triggered by consumer demand and actions by influential environmental groups such as Greenpeace (Reinstaller, 2005). Table I.4 below summarises some of the main environmental changes in the pulp and paper industry in the recent past and their main drivers.

Table I.4. Technology changes underlying environmental performance dynamics in pulp and paper production: 1980-95.(source: Berkhout, 2005).

Indicator	**Key technology drivers of environmental performance change**
CO_2	Background energy mix
Timber use	Product change (higher filler and recycled fibre content in paper), process change (fibre stock recirculation).
NO_x	Energy efficiency (transport), process change (energy efficiency in pulping), background energy mix change
SO_2	Sulphur dioxide abatement (pulping)
BOD (Biological Oxygen Demand)	Abatement (waste water treatment), process change (heat recovery from organic wastes in mechanical pulp), product reformulation (higher recycled fibre use).
COD (Chemical Oxygen Demand)	Waste water treatment
AOX (Absorbable Organic Halogens), including Dioxins	Process change (elemental or total chlorine-free bleaching)

Observed learning curves and economies of scale

'Learning' is observed in the case of the production of chlorine-free (TCF) paper. One of the leading Swedish paper producers, Södra, switched to TCF paper in the early 1990s. It could then sell its TCF paper at a premium to make up for higher production costs. By 2002, however, TCF paper had become "mainstream" and could be produced at the same cost (and with the same quality) as ordinary paper. In this case, learning was company-specific and, in the judgement of the company, slow.

Policy influence on innovation

Sweden: With regards to the chlorine free paper development observed in Sweden (and to a lesser extent the US), environmental policy in the form of emissions standards may have played a role in the diffusion of the technology in Sweden, but only indirectly, as firms might have innovated due to anticipating stricter standards in the future.

Blazejczak and Edler (2000) found that Swedish policy was most innovation-friendly in the pulp and paper sector as it was characterised by a search for consensus in combination with ambitious long-term goals.

Finland: Concerning air and water pollution regulation, the 'regulatory practice' used in Finland has not induced the development of new technologies, as the approach and targets set (using BAT – Best available technology, and limit emission values) could be met by existing abatement technology. Secondly, an integrated pollution prevention and control (IPPC) permit requirement for operators to assess recycling of water and materials may have induced some innovation, but it is concluded that it remains an 'open question' as to whether the innovation occurred as a result of normal commercial practices or as a result of the Finnish policy. Thirdly, although the diffusion of abatement technology was achieved, such diffusion trends were achieved in other nations by other means (such as effluent charges). The regulatory framework therefore seemed to give no benefits over other forms of environmental policy. Finally, it is concluded that R&D requirements in IPPC permits have not had any discernable impact on innovation and diffusion.

Netherlands: No direct association was found between the implementation of environmental policy measures and the number of collective innovation research projects (as an indicator of innovation).the only exception were research projects on energy-efficiency that increased in number in the period 1994-5 after the signing of the first Long Term Agreement on energy-efficiency between government and the industry in 1993 (an interactive policy instrument). One of the reasons for the lack of association is that because of the steady accumulation of new policy measures applicable to the sector, it is difficult to directly link research and specific policy measures.

Finally, the evidence on the relationship between environmental policy instruments and innovation in the pulp and paper sector suggests that of the instruments assessed, none have forced radical innovation. The main drivers of radical changes (TCF paper) have been consumer demand and pressure from environmental groups. Of the evidence reviewed, it suggests that in practice the type of policy instrument that is applied matters less, but that it is the other characteristics of the instruments (intensity, flexibility, dynamic orientation) that matter more. For example, it is noted that the diffusion of waste water treatment plants in Finland (that uses effluent *standards*) was comparable to diffusion processes in other countries, such as the Netherlands, that used other policy instruments (the Netherlands use effluent *charges*). On the other hand, most authors emphasize the importance for innovation of the short-term flexibility and the long-term robustness of the policy measures.

Case Study 5: Substitution of hazardous chemical substances[18]

The technology

This case study investigates the area of reducing the risks that chemical substances may cause for people and the environment, by focusing on substituting away from hazardous chemicals.

Substitution will often involve not just the replacement of one chemical substance by another, less hazardous one, but also other technological and/or organisational changes. Functional equivalence is a key element: if the replacement of the chemical leads to lower product quality or to insurmountable problems with the process, one cannot speak of a (successful) substitution.

What type(s) of policies were assessed?

The replacement of chlorinated solvents in Sweden, Denmark, the US and Germany by less hazardous alternatives is used as an exemplary case for substitution in general. However, prior to assessing policy instruments in these countries it is noted that only Sweden and Denmark have introduced an ‘environmental’ substitution obligation in their legislation (as current European legislation only mandates the substitution principle for occupational and safety cases i.e. excluding environmental protection).

Firstly the Swedish experience is focussed on, where the substitution principle became part of chemicals legislation already in 1973 (Löfstedt, 2003). Since 1999 it is known as

[18] See Oosterhuis (2006b) for the full case study report.

the ‘product choice principle’, one of the cornerstones of the Swedish Environmental Code. A famous example of the application of the substitution principle in Sweden is the ban on trichloroethylene (tri) which was introduced in 1996. The European Court of Justice found this ban to be in agreement with EU law (case C-473/98). Nevertheless, the ban has met with a lot of opposition, on the one hand because a total ban was considered to be disproportional given the relatively minor harmful properties of tri, and on the other hand because many industries argued they had no substitute for tri. Exemptions from the ban were made possible for the latter cases.

Secondly the Danish policy approach is assessed. Danish occupational health and safety legislation, enacted in 2001, requires the replacement of hazardous substances or materials by less hazardous ones. This substitution is compulsory even if the effects of the hazardous substances are insignificant. The law provides for exemptions if substitution is technically impossible or prohibitively expensive. In addition, the Danish Environmental Protection Agency has published a ‘List of Undesirable Substances’. These substances (more than 8,000) are not banned, but their substitution is being encouraged. In 2003, a website was launched (www.catsub.dk) containing more than 200 examples of substitutions in different companies. Substitution of hazardous chemicals in Denmark is also promoted by means of economic instruments. For example, environmental taxes are levied on pesticides, chlorinated solvents, CFCs, nickel-cadmium batteries, soft PVC and phthalates.

Thirdly, the American Massachusetts Toxics Use Reduction Act (TURA) is studied. The 1989 TURA legislation requires that manufacturing firms using specific quantities of approximately 900 industrial chemicals undergo a biyearly process to identify alternatives to reduce waste and the use of those chemicals. Through the toxics use reduction planning process firms understand why they use a specific chemical (what ‘service’ it provides), and how it is used in the production process. They also conduct a systematic search for and comprehensive financial, technical, environmental, and occupational health and safety analysis of viable alternatives. The act instructs firms to identify ways to redesign production processes and products and provides six different methods that ‘count’ as toxics use reduction (Tickner *et al.,* 2005).

Finally the German experience in applying the substitution principle is investigated. The German Ordinance on dangerous substances (*Gefahrstoffverordnung*) states (in 9(1)) that employers should prevent or minimise the dangers to the health and safety of their employees caused by hazardous substances, preferably by substituting the relevant substance. A decision not to substitute has to be justified. The German substitution principle is therefore primarily based on occupational health and safety considerations.

Historical development, stages of innovation, market penetration

Substitution usually pertains to more than just replacing one chemical by another one. The difference in properties between the two substances may create the need for other changes (technical or organisational) as well. The necessity and desirability of substitution will not only depend on the availability, feasibility and costs of the alternative, but also on the function of the hazardous substance in the production chain. More generally, cases of chemical substitution can display a wide range of complexity. The larger the number of users and applications of a substance and the broader the scope of changes involved in the substitution, the more difficult the substitution will be.

Past this, the case study focuses on the individual case study nations/substances rather than on detailing overly technical chemical development, innovation or market penetration. These issues are detailed below.

Observed learning curves and economies of scale

Although empirical evidence on the dynamics of costs and prices in the innovation of chemical substances is more than 20 years old, it may still have relevance as far as the general patterns are concerned.

Lieberman (1984) studied the development of production costs and prices for 37 chemical substances during a period from around 1960 until 1972. He found that learning curves are a function of cumulative output and cumulative investment rather than calendar time. Learning curve effects appeared to be much more important than standard economies of scale, even though the latter play a major role in the chemical industry. For more than half of the sample, the estimated 'learning curve slope' was between 70 and 80%, i.e. the production costs decreased by 20 to 30% for each doubling of cumulative output. The individual learning curves for the 37 substances were remarkably uniform, although there were some small but significant differences. In particular, R&D expenditures (or the underlying technological opportunities) appeared to steepen the learning curve. For the overall sample, prices declined at an average rate of 5.5% per year. In the long term, prices of chemicals closely followed the learning curve, but in the short term market power led to a slow-down in price decreases, as might be expected. To the extent that substitution involves the replacement of hazardous chemicals by less hazardous ones, the evidence on learning curve effects suggests that it may be a self-reinforcing process: growth in production of the alternative implies cost and price reductions, making it more attractive for an increasing number of actors.

Policy influence on innovation

In the Swedish case, when compared to the approaches in other countries, the Swedish tri ban may not have been very effective, as a large number of exemptions to the ban were granted. In Germany, where the emphasis has been on technical standards for equipment and emissions, industry has invested in modern, 'closed' systems for tri use. As a result, the specific emissions of tri per euro of value added in the metal industry in Sweden is now 90 times higher than in Germany, whereas in 1993 it was only 9 times higher (see Table I.5).

Table I.5. Emissions of trichloroethylene in tonnes per € 1 billion of value added in the metal industry.

	1993	2003
Sweden	209	11.6
Germany	24	0.13

(Source: Birkenfeld *et al.*, 2005)

Major reductions in tri use have also been achieved in Norway, where a tax on tri and other chlorinated solvents was introduced in 2000. Purchases of tri in Norway fell from more than 500 tonnes in 1999 to 82 tonnes in 2000 and 139 in 2001 (after Sterner, 2004). This reduction is thought to have been driven by efforts to cut leakage and boost recycling, as well as through substitution (ENDS, 2003). The tri example from Sweden thus suggests that imposing chemical substitution by means of a general ban with exemptions may lead to less environmental innovation than stimulating substitution by means of financial incentives or regulations aimed at limiting exposure and emissions.

In the Danish case, regarding the environmental taxes which are levied on hazardous chemicals there is some evidence for the effectiveness of these taxes (Ecological Council, 2002). According to a Danish cable producer, which has replaced PVC with phthalates by halogen-free polymers in part of its products, the taxes on PVC and phthalates have helped to lessen the price difference (Ecological Council, 2006). The tax on chlorinated solvents, though much lower than the Norwegian tax on the same substances, contributed to a decrease in the use of these substances by 60% (Sterner, 2004).

In the case of the US TURA experience, between 1990 and 2000 some 550 firms that continuously participated in the program have reduced the use of the targeted toxic chemicals by 40% (Tickner and Geiser, 2004, Appendix A). According to O'Rourke and Lee (2004), mandatory planning, new mechanisms of accountability and improved processes of learning have all been critical to TURA's success in motivating firms to innovate for the environment. The TURA program has designated tri as one of five high priority substances that are to receive special attention, with the aim of attaining significant reduction in use. In 2004 a project was started, targeted at smaller businesses using tri, who do not have direct access to pollution prevention information and resources (TURI, 2006). Spin off programmes with the aim of widening participation, can be seen as being a testament to the successful nature of the TURA programme.

As indicated above, the German approach to chlorinated solvents has differed from the approach taken in Sweden (a ban with exemptions) and Denmark (taxation). Rather than seeking a reduction in the use of the hazardous substances per se, the German approach focused on risk reduction through the introduction of 'closed' systems for the use of chlorinated solvents. As a result of this policy, Germany not only achieved substantial decreases in solvent use, but also became a leading exporter of high-quality closed-loop degreasing equipment (Sterner, 2004). This can be seen as an illustration of 'first mover advantages' and the famous 'Porter hypothesis' (Porter and Van der Linde, 1995).

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